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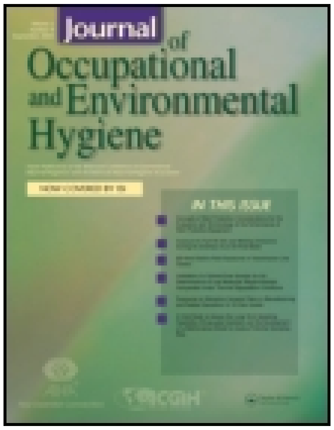

Journal of Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uoeh20

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Accepted author version posted online: 02 Jan 2012.Published online: 24 Feb 2012.

To cite this article: Marcy L. McNamara, Erin O. Semmens, Steven Gaskill, Charles Palmer, Curtis W. Noonan & Tony J. Ward (2012) Base Camp Personnel Exposure to Particulate Matter During Wildland Fire Suppression Activities, Journal of Occupational and Environmental Hygiene, 9:3, 149-156, DOI: 10.1080/15459624.2011.652934

To link to this article: http://dx.doi.org/10.1080/15459624.2011.652934

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Journal of Occupational and Environmental Hygiene, 9: 149–156
ISSN: 1545-9624 print / 1545-9632 online
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DOI: 10.1080/15459624.2011.652934

Base Camp Personnel Exposure to Particulate Matter During Wildland Fire Suppression Activities

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Wildland fire base camps commonly house thousands of support personnel for weeks at a time. The selection of the location of these base camps is largely a strategic decision that incorporates many factors, one of which is the potential impact of biomass smoke from the nearby fire event. Biomass smoke has many documented adverse health effects due, primarily, to high levels of fine particulate matter ($PM_{2.5}$). Minimizing particulate matter exposure to potentially susceptible individuals working as support personnel in the base camp is vital. In addition to smoke from nearby wildland fires, base camp operations have the potential to generate particulate matter via vehicle emissions, dust, and generator use. We monitored particulate matter at three base camps during the fire season of 2009 in Washington, Oregon, and California. During the sampling events, 1-min time-weighted averages of $PM_{2.5}$ and particle counts from three size fractions (0.3–0.5 microns, 0.5–1.0 microns, and 1.0–2.5 microns) were measured. Results showed that all PM size fractions (as well as overall $PM_{2.5}$ concentrations) were higher during the overnight hours, a trend that was consistent at all camps. Our results provide evidence of camp-based, site-specific sources of $PM_{2.5}$ that could potentially exceed the contributions from the nearby wildfire. These exposures could adversely impact wildland firefighters who sleep in the camp, as well as the camp support personnel, who could include susceptible individuals. A better understanding of the sources and patterns of poor air quality within base camps would help to inform prevention strategies to reduce personnel exposures.

Keywords air quality, $PM_{2.5}$, wildland fire

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INTRODUCTION

Multiple studies have focused on health effects of biomass smoke exposure on wildland firefighters.(1–8) However, there is a lack of studies that have focused specifically on base camp exposures. In proximity to wildland fires, base camps are designed to temporarily house up to several thousand members of incident command and support personnel as well as provide safe sleeping conditions for wildland firefighters. While firefighters are generally healthy and physically fit, incident command and support personnel present at the camp at all hours may include individuals with respiratory or cardiovascular conditions, making them potentially more susceptible to the adverse health effects of air pollution.(9) Base camps are also crucial for centralized administrative services, such as communications, planning, logistics, safety, and finance.

Biomass smoke is a complex mixture of multiple components that have well-documented adverse human health effects.(10,11) Commonly detected pollutants in biomass smoke include polycyclic aromatic hydrocarbons (PAHs)(12) as well as regulated criteria pollutants, such as particulate matter with an aerodynamic diameter of 2.5 microns or less ($PM_{2.5}$), carbon monoxide (CO), and nitrogen oxides. A comprehensive review by Naeher et al.(10) concluded that $PM_{2.5}$ serves as the best exposure metric for wood smoke and tends to be among the most elevated in relation to existing air quality standards. Particle source and size can alter the extent of resulting inflammatory responses,(13) and multiple epidemiologic studies have found differing health effects based on particle size, with ultrafine particles typically associated with more severe adverse health effects than larger particles.(14,15)

Alterations in weather patterns such as warmer temperature trends brought about by global climate change can influence the frequency and duration of wildland fires.(16) Warmer temperatures have also contributed to the size and severity of the mountain pine beetle outbreak, which in the western United States alone is estimated to have killed over 2 million acres of coniferous trees, thereby leaving standing fuel for future forest fires.(17) Coupled together, these warmer temperatures and increased fuel loads in our forests are providing for increased risks of large wildland fires. As a result, exposure of wildland firefighters, incident command and support personnel, and residents of nearby communities to biomass smoke will likely increase.

Independent of location, base camps often have specific and common air pollution sources. In addition to wood smoke and dust, these camps frequently require generators as a reliable power source for equipment and overnight lighting. Depending on size and frequency of use, these diesel generators can be large sources of both PM and CO. In this article we present the results of an air monitoring study designed to characterize base camp PM concentrations during forest fire events. During the summer of 2009, we measured 1-min time-weighted averages (TWAs) of $PM_{2.5}$ concentrations as well as particle counts by size fraction at fire camps in Washington, Oregon, and Southern California.

METHODS

Instruments Used

TSI DustTrak 8530 (TSI Inc., Shoreview, Minn.)

The DustTrak is a real-time optical scattering instrument that measures particulate matter in the airflow by the extent of forward scattering of an infrared diode laser beam. They are factory calibrated to the respirable fraction of standard ISO 12103–1, A1 test dust (formerly Arizona Test Dust). DustTraks were zeroed and the impaction plate was cleaned and greased/oiled as necessary prior to each sampling event. Data were recorded as 1-min TWAs.

Lighthouse Handheld 3016 IAQ Particle Counter (Lighthouse Worldwide Solutions, Fremont, Calif.)

The contributions of multiple size fractions to overall $PM_{2.5}$ levels were determined with a real-time particle counter that identifies individual particle size fractions (0.3–0.5 microns, 0.5–1.0 microns, and 1.0–2.5 microns). Results are displayed as particle counts in the specified size channel. Air is pulled through the instrument at 2.8 L/min, and data are recorded as 1-min TWAs.

Camp/Site Selection

Fire camps were selected for sampling based on the presence of an actively burning fire, and convenience of location. Three fire camps were sampled over a 9-day period during August 2009. All fire camp information was gathered on location or from the Incident Information System website. Fire smoke was not an observable pollutant via sight or smell at any of these three camps during the air sampling periods. We observed that traffic patterns within the camp were highest during transportation of the wildland firefighters to and from the fire line in the early morning (~06:00) and evening (~20:00). Power in all camps was solely derived from multiple generators used around the clock for communication equipment, lighting, and food preparation.

Discovery Fire Camp, Naches, Washington

The Discovery fire burned 4178 acres in Wenatchee and Snoqualmie National Forests, 30 miles west of Yakima, Washington. The fire was started by lightning on July 28 and was contained on August 12. At peak activity, there were approximately 800 personnel in the camp. This camp had two designated sampling sites due to major differences in activity and potential particle sources at the two sites. Site 1 was in the supply area, in proximity to a dirt road as well as a diesel-powered generator. Site 2 was centrally located in camp behind the briefing tent, more than 100 feet from the nearest generator or used roadway. Air sampling took place at Site 1 from 09:45 on August 9 to 16:18 on August 10 (30 hr, 33 min). Site 2 sampling began at 09:30 on August 9 and concluded at 13:57 on August 10 (28 hr, 27 min). Both sites were monitored with one DustTrak 8530 and one particle counter.

Williams Creek Fire Camp, Glide, Oregon

The Williams Creek fire burned 8395 acres 15 miles east of Glide, Oregon, in the Umpqua National Forest. The fire began on July 28 (cause not determined) and was contained on August 16. Base camp was located in an open field, where approximately 250 personnel were headquartered. Air sampling took place from August 12 at 09:40 to August 14 at 08:56 (47 hr, 16 min). Sampling took place in the central command area more than 500 feet from any generator. Air quality was monitored with one DustTrak 8530 and one particle counter.

La Brea Fire Camp, San Luis Obispo, California

A cooking fire at a marijuana drug trafficking operation started the La Brea fire on August 8 and burned 89,489 acres 21 miles east of Santa Maria before it was contained on August 22. This camp had two sampling locations based on the presence of a remote "spike camp" located closer to the fireline. Spike camps are areas set up to provide firefighters a place to stay out in the forest while they are fighting the fire. Sampling in the base camp took place in proximity to a heavily used dirt road as well as several diesel-powered generators. The spike camp was located approximately 30 miles by road from the main camp, where only wildland firefighters were allowed. Air sampling took place at the base camp from 09:45 on August 16 to 12:04 on August 17 (26 hr, 9 min) and at the spike camp from 20:00 (August 16) to 13:25 on August 17 (17 hr, 25 min). Air quality was monitored at both sites with one DustTrak 8530 and one particle counter.

Day/Night Characterization

"Day" exposures (09:01–17:00) were chosen to correspond with the portion of the day after the wildland firefighters departed camp and only base camp personnel were present in the camp. "Night" exposures (17:01–09:00) correspond with the remainder of the 24-hr period when all base camp personnel and wildland firefighters were present in the camp. Multiple sensitivity analyses were conducted for different time designations for day and night to ensure there was no cut point bias. Expanding "day" classification to start earlier (05:00–17:00) or end later (09:01–20:00) had no impact on the statistical significance of our results or on overall conclusions.

Data Analysis

All data were downloaded onto a PC using TrakPro and LMS Exchange software for the DustTrak and particle counter, respectively. Microsoft Excel was used for determining the average, standard deviation, and 95% confidence interval of the difference between the means for the DustTrak data, while particle counter data were imported into SAS (version 9.2) for statistical analyses. T-tests were performed to investigate potential significant differences according to site and time of day ($\alpha = 0.05$). The 95th percentile of each size fraction per sampling site was calculated, and the frequency of observations above this level for each sampling event was determined.

RESULTS

DustTrak Results

Table I presents the average, standard deviation, minimum, and maximum values of $PM_{2.5}$ measured during each of the sampling events. The location with the highest levels of $PM_{2.5}$ measured throughout the sampling periods was the La Brea Base Camp, with an average concentration of 41.3 μg/m^3 throughout the 26-hour sampling period. With the exception of the La Brea Base Camp, all averaged $PM_{2.5}$ levels were below the U.S. Environmental Protection Agency (EPA) 24-hr National Ambient Air Quality Standard (NAAQS) of 35 μg/m^3, although the La Brea Spike Camp was very close (34.6 μg/m^3 average during 15-hr, 25-min sampling period). The highest spike measured during the sampling events (either during the day or night) was 309 μg/m^3 at Discovery Camp Site 1. This event was measured at 10:31 on August 10 and was likely caused by a dust plume from a vehicle on the nearby dirt road, or the wind directing the exhaust from the nearby diesel generator over the sampling equipment.

In an effort to see the temporal trends of $PM_{2.5}$ within the base camps, Figures 1–3 present the real-time data from each sampling location. Shaded areas represent night (17:01–09:00) and unshaded areas represent day (09:01–17:00). At each of the camps, $PM_{2.5}$ concentrations were more elevated at night compared with the day sampling periods. At Discovery Camp Site 2, there were elevated levels measured during the nighttime hours for the first half of sample collection, with levels dropping off during the day. This overall pattern was not repeated during the second night sample at the Discovery Camp Site 2 (Figure 1, gray).

We saw a similar pattern at the La Brea Base Camp (Figure 3, black). At La Brea Spike Camp (Figure 3, gray), there were frequent, distinct high spikes of $PM_{2.5}$ throughout the night that were not measured in sampling conducted during the day. Table I illustrates the consistently higher $PM_{2.5}$ concentrations during night periods for the sampling sites, ranging from minor differences (1 μg/m^3 (95% confidence interval [CI]: 0.6–1.4) at Williams Creek) to substantial differences (11.1 μg/m^3 (95% CI: 8.7–13.7) at the La Brea Spike Camp.

Particle Count Results

To further investigate the trends in relative contributions of individual components of $PM_{2.5}$, a particle counter was used to examine three $PM_{2.5}$ size fractions: 0.3–0.5 microns, 0.5–1.0 microns, and 1.0–2.5 microns. Figure 4 presents the average log concentrations of particle counts in each of the size fractions, and Table II presents the average concentrations of particles (particles/cm^3) in each of the size fractions. At each of the sites, the 0.3–0.5 micron fraction had the greatest number (data not shown) and concentration of particles, followed by the 0.5–1.0 micron fraction. Similar to the $PM_{2.5}$ results, a significant difference was found between the day and night periods in all size fractions, with night particle counts elevated at all camps and sites ($p < 0.05$ for 0.5–1.0 micron fraction at Discovery Camp Site 1; all other $p < 0.0001$) (Figure 4).

TABLE I. Summary of $PM_{2.5}$ Sampling Data

	Sample Duration (d:hh:mm)^A	Average μg/m^3 (SD)	Maximum μg/m^3 (Date, Time)	Day Average μg/m^3 (SD)	Night Average μg/m^3 (SD)	Night-Day Difference (μg/m^3)	95% CI of Difference (μg/m^3)
Discovery Site 1	1:06:33	21.2 (14.7)	309 (8/10/09, 10:31)	17.3 (14.1)	24.6 (14.3)	7.3	6.04–8.56
Discovery Site 2	1:04:27	8.8 (6.7)	46 (8/10/09, 07:23)	4.67 (3.15)	11.0 (7.0)	6.33	5.86–6.80
Williams Creek	1:23:26	12.0 (5.0)	81 (8/13/09, 16:41)	11.3 (5.4)	12.3 (4.8)	1	0.61–1.39
La Brea Base	1:02:19	41.3 (11.2)	93 (8/17/09, 08:11)	37.1 (14.6)	44.0 (7.0)	6.9	5.82–7.98
La Brea Spike	15:25	34.6 (14.4)	110 (8/17/09, 01:48)	25.2 (3.2)	36.4 (15.0)	11.2	8.74–13.66

^{A}In d:hh:mm, recorded as 1-min TWAs.

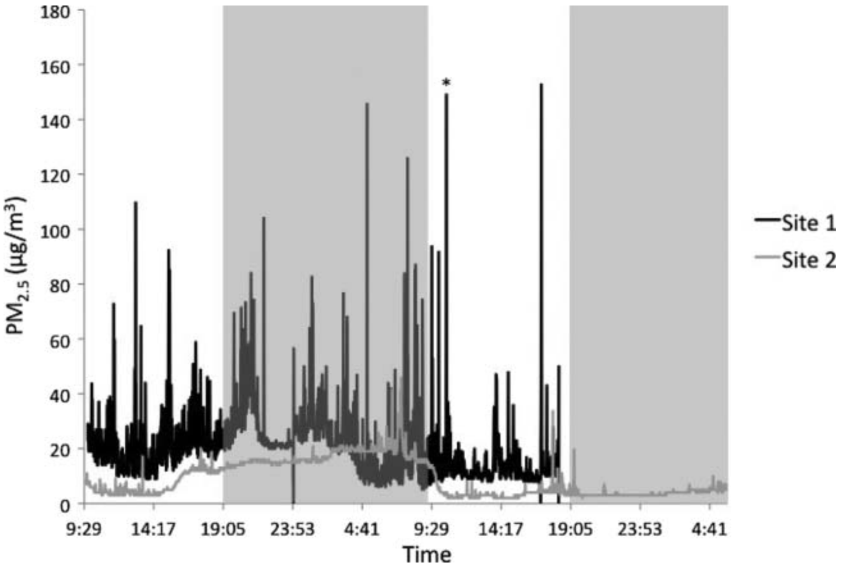

FIGURE 1. One-minute TWA $PM_{2.5}$ data Discovery Base Camp Site 1 (black) and Site 2 (gray). Shaded areas approximately represent night (17:01–09:00), and unshaded areas represent day (09:01–17:00). One data point was modified to 150 μg/m^3 to fit scale: spike at 10:31 (denoted with *) was originally recorded as 309 μg/m^3. Site 1 and Site 2 averages: 21.2 and 8.8 μg/m^3, respectively.

Similar to the $PM_{2.5}$ spikes measured during the sampling events, we were interested in assessing elevated exposure events for each of the size fractions. The 95th percentile for each size fraction was determined for each complete sampling period (including day and night), with Table III presenting the frequency of observations (%) above the 95th percentile. For each size fraction at nearly all sites there was a greater percentage of observations above the 95th percentile during the night periods compared with the day periods.

DISCUSSION

This report investigates base camp exposures to $PM_{2.5}$, including three different size fractions within the fine fraction. We found a consistent trend of higher levels of $PM_{2.5}$ overnight at all locations at all camps (Table I). These findings are in agreement with an unpublished report focused on particulate matter with an aerodynamic diameter of less than 10 microns (PM_{10}) that found very high concentrations (>1000

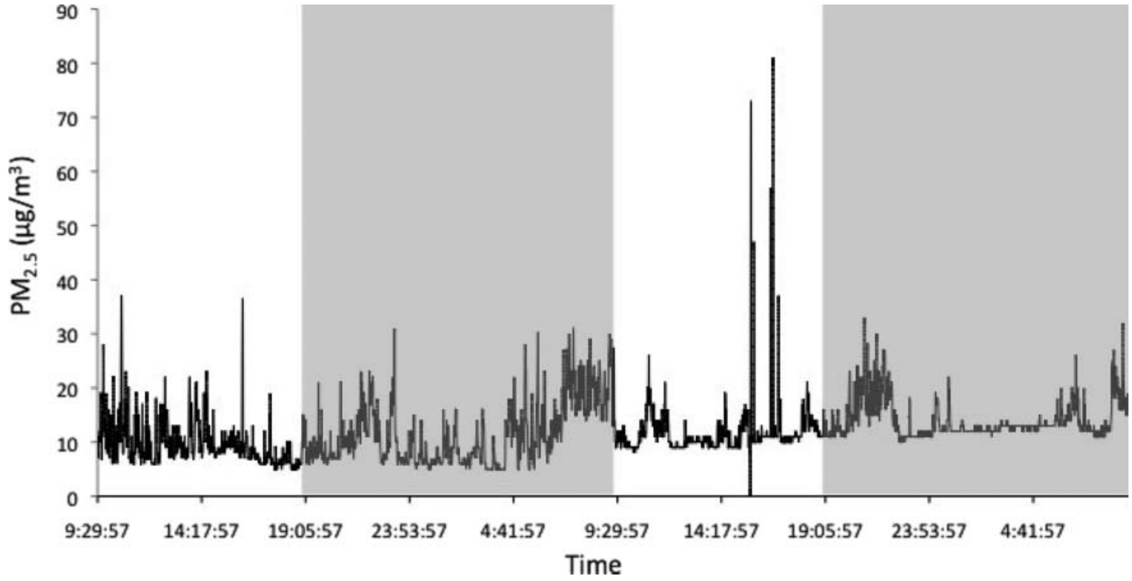

FIGURE 2. One-minute TWA $PM_{2.5}$ data at Williams Creek Base Camp. Shaded areas approximately represent night (17:01–09:00), and unshaded areas represent day (09:01–17:00). Average: 12.0 μg/m^3.

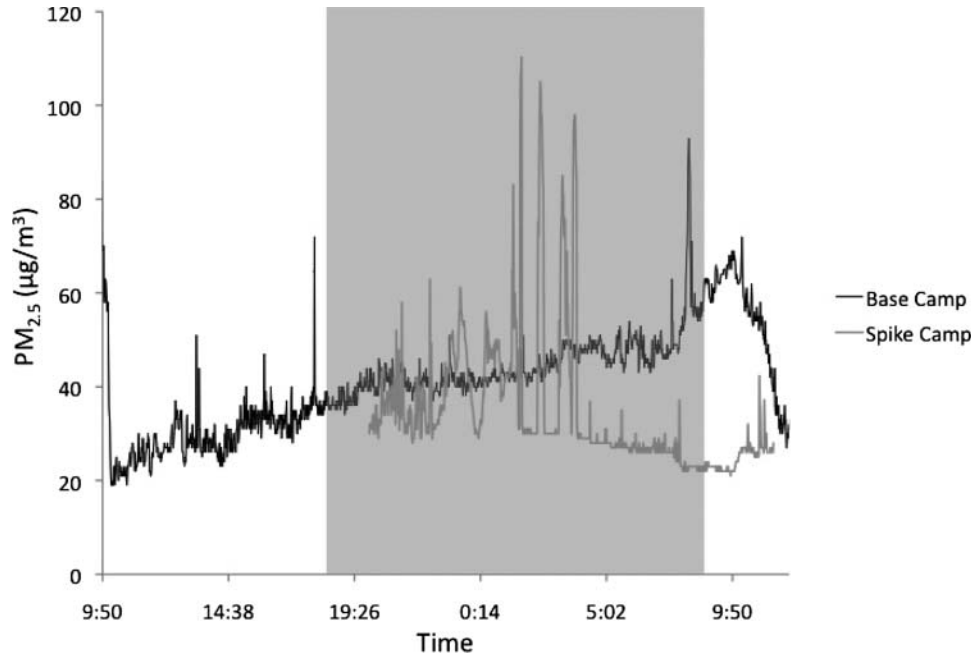

FIGURE 3. One-minute TWA $PM_{2.5}$ data at La Brea Base Camp (black) and Spike Camp (gray). Shaded areas approximately represent night (17:01–09:00), and unshaded areas represent day (09:01–17:00). Base and Spike Camp averages: 41.3 and 34.6 $\mu g/m^3$, respectively.

$\mu g/m^3$) overnight vs. during the day in a Pacific Northwest Fire camp.[18] The concentrations of $PM_{2.5}$ measured in all the camps were substantially below respirable particulate exposures experienced by wildland firefighters actively fighting a fire, which has been reported to reach an average of 1.11 mg/m^3 with a maximum of 2.46 mg/m^3.[8] Generally speaking, $PM_{2.5}$ concentrations were below the 24-hr NAAQS established by the EPA (35 $\mu g/m^3$). Only the La Brea Base

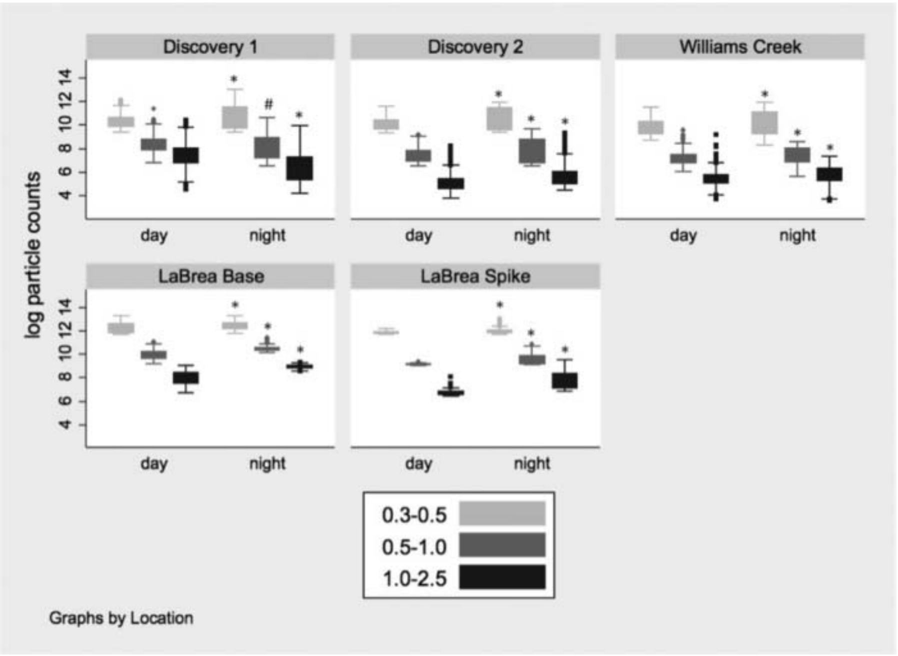

FIGURE 4. Log particle counts by size fraction (0.3–0.5, 0.5–1.0, 1.0–2.5 microns) during day (09:01–17:00) and night (17:01–09:00) at base camps. $*$ represents $p < 0.001$, and # represents $p < 0.05$ in t-tests comparing individual size fractions during the day vs. night.

TABLE II. Particle Concentrations by Location and Size Fraction

	0.3–0.5 μm	0.5–1.0 μm	1.0–2.5 μm
Discovery Site 1	14.04 (13.59–14.52)	1.41 (1.36–1.46)	0.30 (0.29–0.32)
Discovery Site 2	12.47 (12.08–12.88)	0.84 (0.81–0.87)	0.08 (0.08–0.08)
Williams Creek	9.24 (8.93–9.57)	0.57 (0.55–0.58)	0.10 (0.09–0.10)
La Brea Base	82.75 (81.11–84.42)	10.34 (10.14–10.53)	1.85 (1.79–1.90)
La Brea Spike	56.95 (56.08–57.84)	4.90 (4.77–5.02)	0.77 (0.74–0.81)

Note: GM (95% CI) in particles/cm^3.

Camp had overall $PM_{2.5}$ levels exceeding the 24-hr standard, with an average concentration of 41.3 μg/m^3 during the more than 1-day sampling period. The larger size of the La Brea camp (~2500 personnel vs. ~800, and ~250 personnel in Discovery and Williams Creek base camps, respectively) likely contributed to the higher levels of $PM_{2.5}$, as larger camps have increased vehicle traffic and therefore more $PM_{2.5}$ from vehicular emissions(19) and road dust.(20)

In addition, larger camps require more power sources and generator use, which is also an established source of $PM_{2.5}$.(21) DustTraks have been documented to overreport PM compared with Federal Reference Methods in source-specific scenarios.(22–24) As the wildland fire camps have diverse sources of $PM_{2.5}$, we chose not to correct our DustTrak data with a wood smoke-specific correction factor.(25)

In addition to $PM_{2.5}$ mass, it is important to consider the sizes of the particles to which base camp workers are being exposed. Emissions from forest fires have a greater proportion of particles ≥ 0.1 μm(26) compared with anthropogenic sources, such as diesel and industrial emissions, which are typically made up of ~80% ultrafine particles (< 0.1 μm).(27) The burning of fuels common to fire-prone U.S. ecosystems results in a unimodal $PM_{2.5}$ distribution within the 0.010–0.450 micron range.(28) Particles emitted from diesel and gasoline engines have been shown to have a dominant mode at about <0.006 microns with a minor mode at about 0.040 microns.(29)

TABLE III. Frequency (%) of Observations Occurring Above 95% Percentile for Respective Particle Sizes

	0.3–0.5 μm	0.5–1.0 μm	1.0–2.5 μm
Discovery Site 1			
Day	0.97	4.55	5.95
Night	7.77	5.35	4.40
Discovery Site 2			
Day	0.11	0.68	2.50
Night	7.41	7.13	6.24
Williams Creek			
Day	0	2.25	4.71
Night	7.45	6.35	5.16
La Brea Base			
Day	9.59	1.14	0
Night	2.08	7.50	8.23
La Brea Spike			
Day	0	0	0
Night	5.94	5.94	5.94

While it is challenging to compare our particle count data with other published studies that use different instruments and sampling methods, our values are relatively similar to those reported in previously published studies also utilizing a particle counter to follow real-time changes in particle counts. Brauer et al.(30) reported a geometric mean of 1.8 and 4.0 particles/cm^3 in the 0.3–0.5 and 0.5–1.0 micron size fractions, respectively, using a Biotest Diagnostics particle counter with the same flow rate as the Lighthouse particle counter (2.8 L/min). Our particle concentration values were lowest at Williams Creek Base Camp and highest at La Brea Base Camp, with geometric means ranging from 9.2 to 82.7 particles/cm^3 in the 0.3–0.5 micron fraction range and from 0.56 to 10.3 particles/cm^3 in the 0.5–1.0 micron fraction (Table II).

Another study using yet another particle counter investigated the 0.5–1.0 micron fraction and found an average of 8 particles/cm^3, with spikes as high as 53 particles/cm^3.(31) A study of ambient pollution found a particle concentration of 4.6 particles/cm^3 when monitoring particles in the 0.5–15 micron fraction.(32) Our reported values are, on average, higher than these published studies, which could reflect real elevations in particle concentration at our sampling locations or may be partially due to instrumentation differences.

The diurnal variation seen in the $PM_{2.5}$ data was also found to be significant in all the size fractions measured with the particle counter (Figure 2). There is no current ambient or occupational standard regarding particle counts; therefore, to investigate elevated exposure events we determined the 95th percentile for each size fraction for each sampling event. Exposure events occurring above the 95th percentile have commonly been used to determine the upper limit of allowable exposure in occupational settings(33) and have also helped classify "elevated" events in previous ambient air pollution studies.(34) There is a more drastic increase in observations above the 95th percentile at night in the 0.3–0.5 micron size fraction, with observations occurring 8 and 67 times more frequently at night at Discovery Camp Sites 1 and 2, respectively. Similarly, at Williams Creek Camp there were zero observations above the 95th percentile during the day, while 7.45% of the night observations spiked above the 95th percentile (Table III). This trend is evident, though not as strong, in the 0.5–1.0 micron size fraction.

CONCLUSIONS

Exposures to forest fire smoke are challenging to assess because smoke exposures are typically sporadic, short-lived, sensitive to meteorology, and rare in areas of high-density population.(35) It is important to focus on base camps, as this is where potentially hundreds, if not thousands, of support personnel reside full time for up to weeks at a time. Importantly, these camp personnel include a range of individuals that could include susceptible populations (e.g., support personnel with respiratory or cardiovascular conditions) compared with the relatively healthy wildland fire worker.

Base camp is also the predominant location of command and control forest fire personnel, and any exposures that could adversely impact executive function and decision making in high stress environments should be well understood. A recent Health Hazard Evaluation Report from the National Institute for Occupational Safety and Health (NIOSH) investigated CO exposure in wildland fire base camps.(36) Among their conclusions was a recommendation to develop a base camp air monitoring program to measure base camp employees' exposure to particulates in addition to CO.

Our study provides a snapshot into the PM exposures experienced by wildland firefighters and support personnel and demonstrates the increased nighttime levels of $PM_{2.5}$ in multiple base camps. In addition, these data provide information on potential sources of base camp air quality. Although we cannot confidently identify the exact sources of these particles solely by their size distribution, the real-time $PM_{2.5}$ data (Figures 1–3), as well as the frequency of spikes above the 95th percentile (Table III) at night, suggest that there is a camp-based, activity-dependent source of $PM_{2.5}$. This is opposed to the sustained levels of $PM_{2.5}$ one would expect if the camp were inundated with a blanket of biomass smoke.

Although the confidence intervals of the difference of the mean day-night values are quite narrow given the standard deviations (Table I), the increased levels of $PM_{2.5}$ at night are consistent at all camps. Correlation between the two sampling sites at Discovery Camp was very low ($r^2 = 0.05$), also suggesting there are location-specific sources of $PM_{2.5}$ within camps. These location-specific sources may or may not be in proximity to the sleeping areas, depending on the layout of the camp. Camp-based sources include vehicle emissions, road dust, and diesel generator exhaust. The use of industrial-scale as well as smaller portable diesel generators has the potential to have a drastic impact on fire camp air quality, especially in situations where employees are working and sleeping in proximity to the generators. The use of such devices is higher during nighttime hours to power lighting and devices related to food preparation.

To further evaluate base camp exposures, additional sampling locations upwind of the base camps (fence line sampling), as well as the collection and analysis of meteorological conditions, including wind direction and wind speed, would be recommended. Determining sources of $PM_{2.5}$ in base camps is the first step toward establishing prevention strategies applicable beyond wildland firefighters to thousands of potentially susceptible support personnel.

ACKNOWLEDGMENTS

This research was in part funded by the Missoula Technology and Development Center (Missoula, Mont.) and the U.S. Forest Service, with core support provided under a grant from the National Center for Research Resources. The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the U.S. Department of Agriculture or U.S. Forest Service.

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